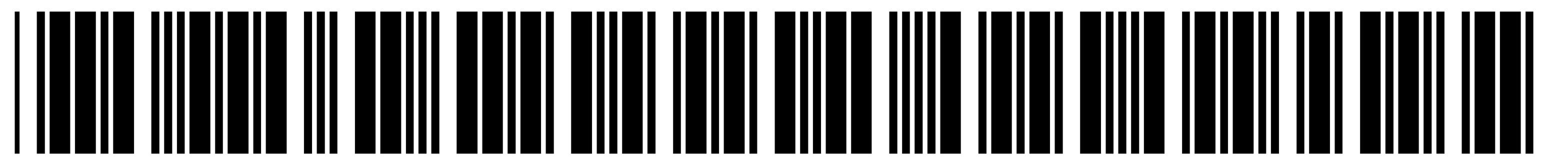
US005853959A

United States Patent [19]

Brand et al.

[11] Patent Number: 5,853,959
[45] Date of Patent: Dec. 29, 1998

[54] **METHOD OF FABRICATING A CONTOURED SLIDER SURFACE FEATURE WITH A SINGLE MASK**

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[73] Assignee: **Seagate Technology, Inc.**, Scotts Valley, Calif.

[21] Appl. No.: **695,374**

[22] Filed: **Aug. 9, 1996**

[51] **Int. Cl.**[6] **G03C 5/00**

[52] **U.S. Cl.** **430/320**; 430/396; 216/22; 216/41; 216/58; 29/630.2; 29/630.18; 29/630.15; 29/630.12

[58] **Field of Search** 430/320, 396, 430/929; 29/603.2, 603.18, 603.15, 603.12; 216/22, 41, 58

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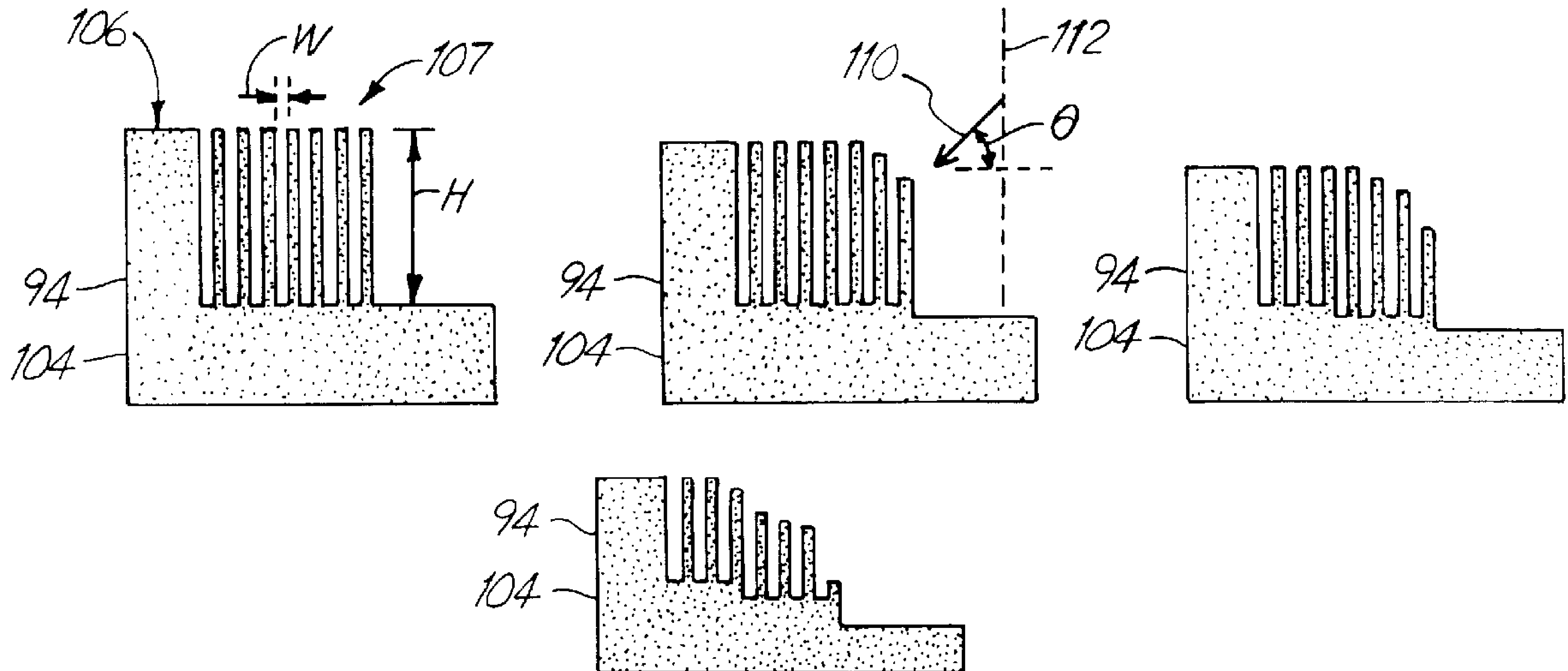
Primary Examiner—M. Nuzzolillo
Assistant Examiner—Steven H. VerSteeg
Attorney, Agent, or Firm—Westman, Champlin & Kelly, P.A.

[57] **ABSTRACT**

A method of fabricating a contoured surface feature to multiple depths on a surface of a hydrodynamic bearing slider with a single mask includes applying a lithographic resist layer to the slider surface and forming the single mask with a mask pattern which includes a masked area, an unmasked area and an intermediate area between the masked area and the unmasked area. The lithographic resist layer is then exposed through the single mask and removed as a function of exposure to form a patterned resist layer and to thereby uncover portions of the slider surface within the patterned resist layer. The uncovered portions of the slider surface and the patterned resist layer are etched, with the uncovered portions being etched to a first depth below the slider surface. The multiple depth surface feature is created by providing the intermediate mask area with a geometry of masked and unmasked features that is unresolvable by one of the steps of exposing an etching such that an area of the slider surface corresponding to the intermediate mask area is etched to a second depth which is less than the first depth.

26 Claims, 7 Drawing Sheets



10
14
22
30
18
24
12
28
20
26
26
16
28

Fig. 1

52
56
54
68
D1

Fig. 3

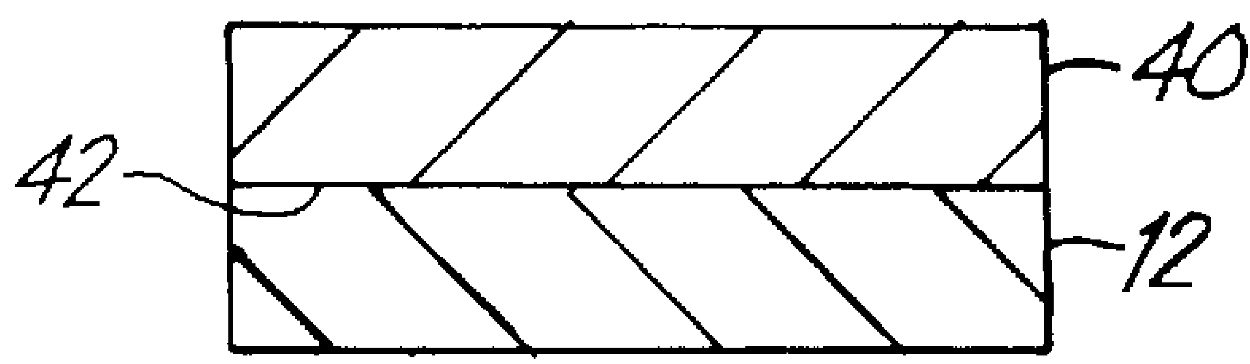


Fig. 2A

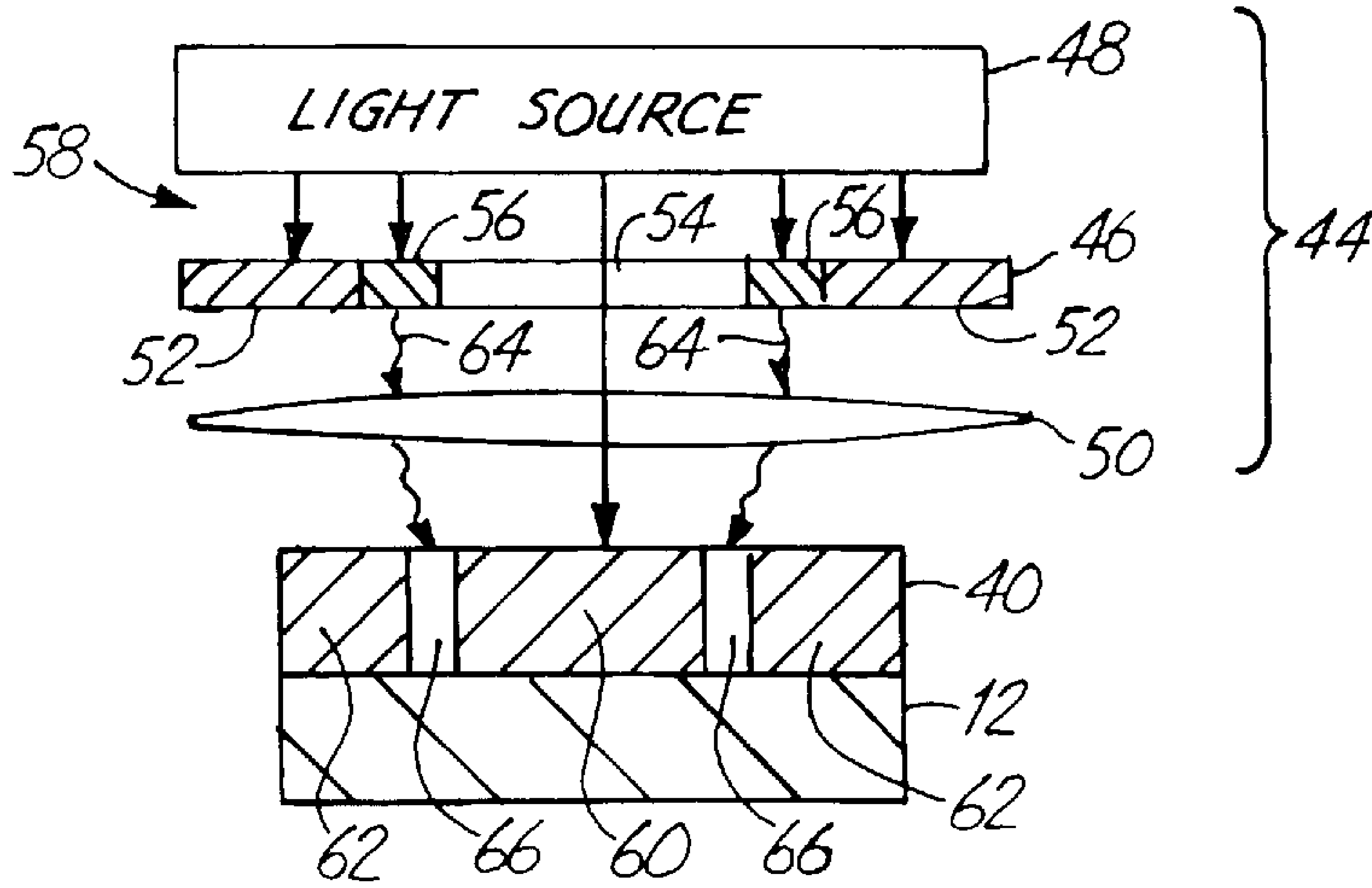


Fig. 2B

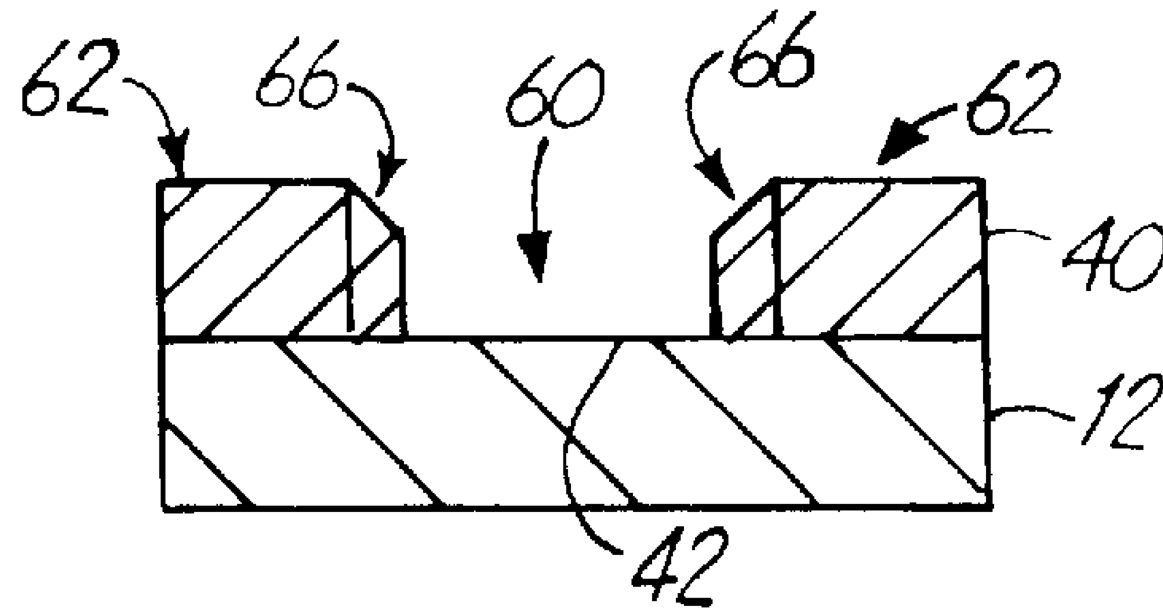


Fig. 2C

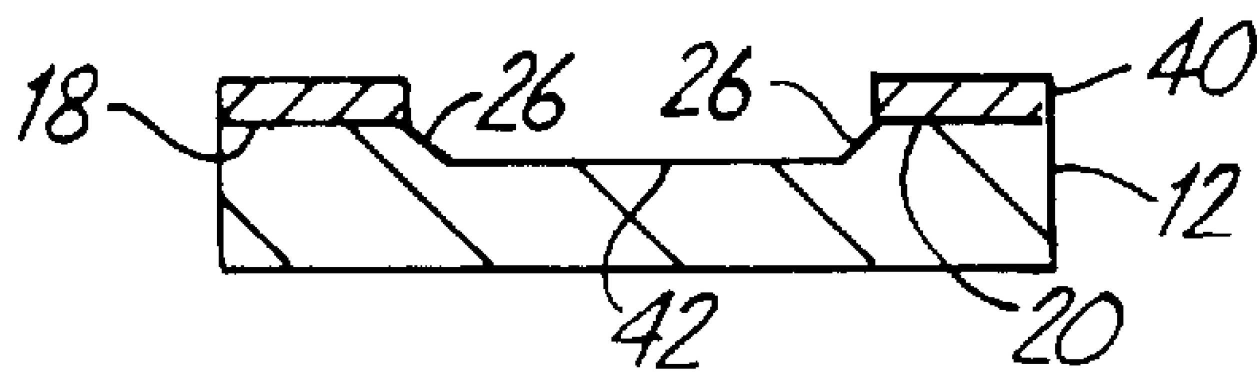


Fig. 2D

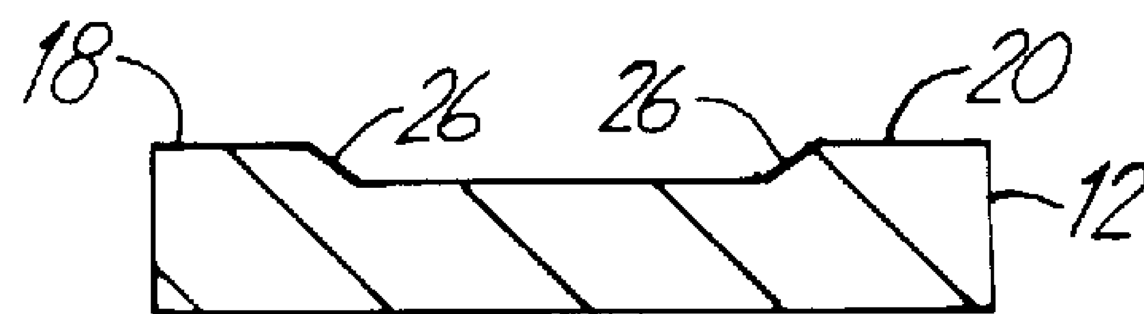


Fig. 2E

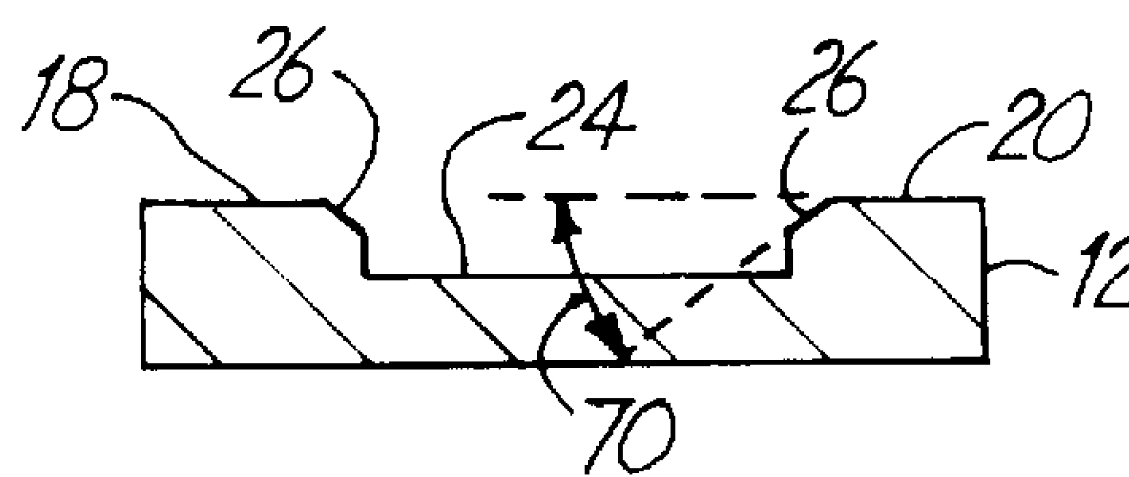


Fig. 2F

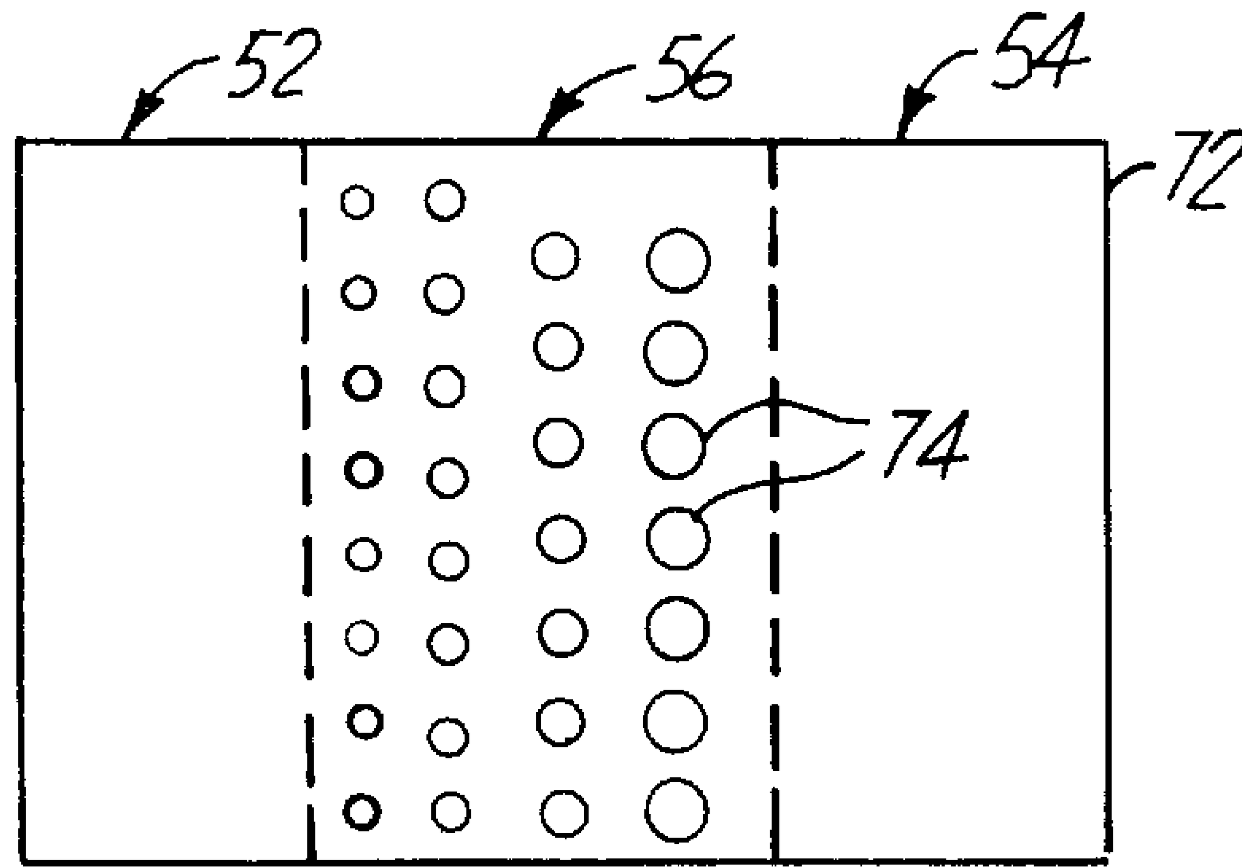


Fig. 4A

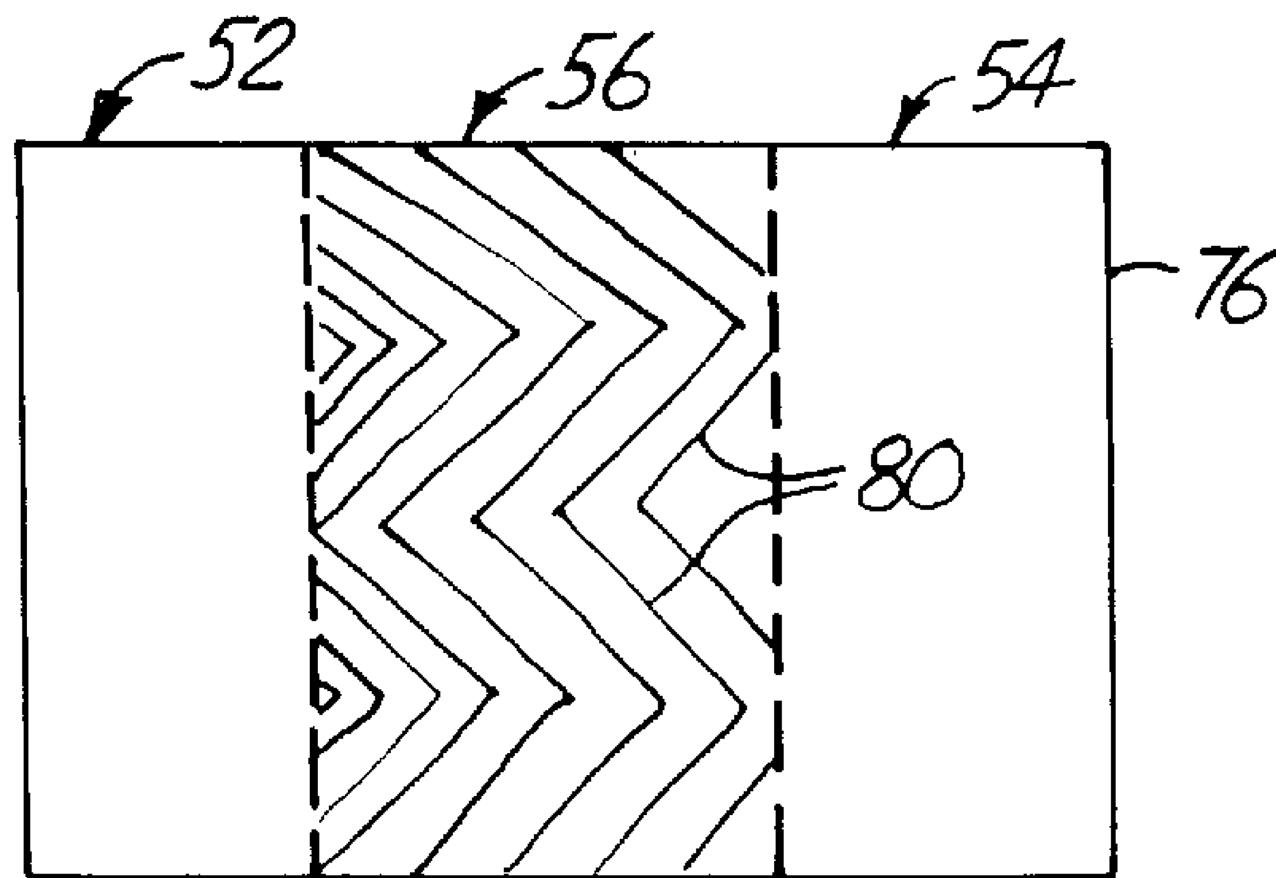


Fig. 4B

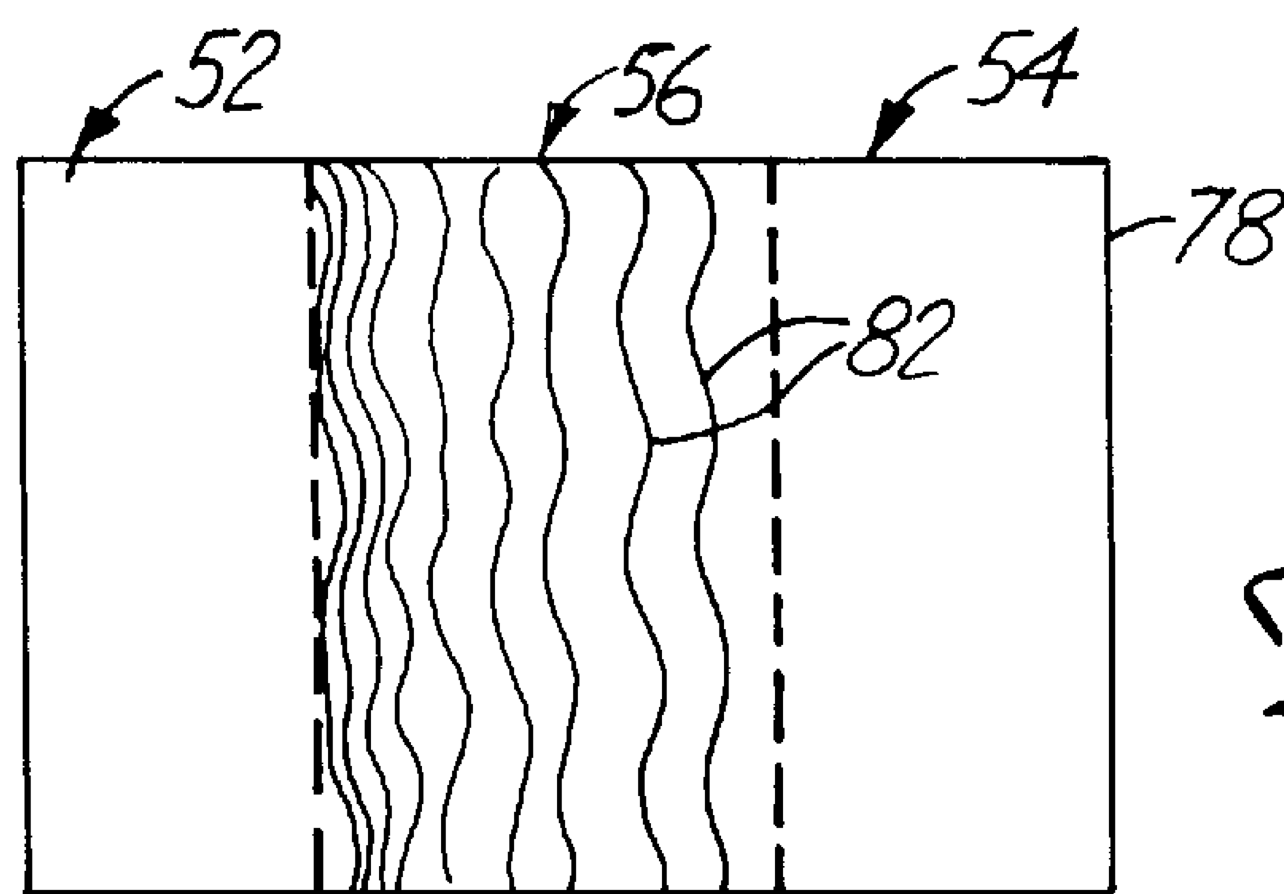


Fig. 4C

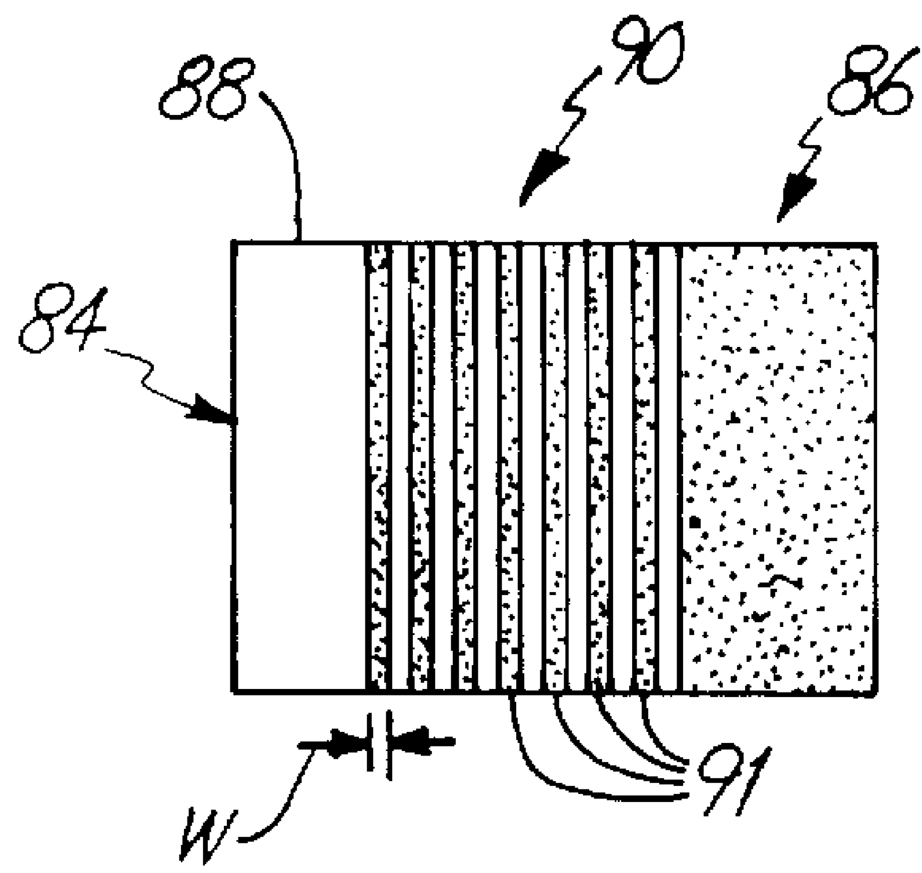


Fig 5A

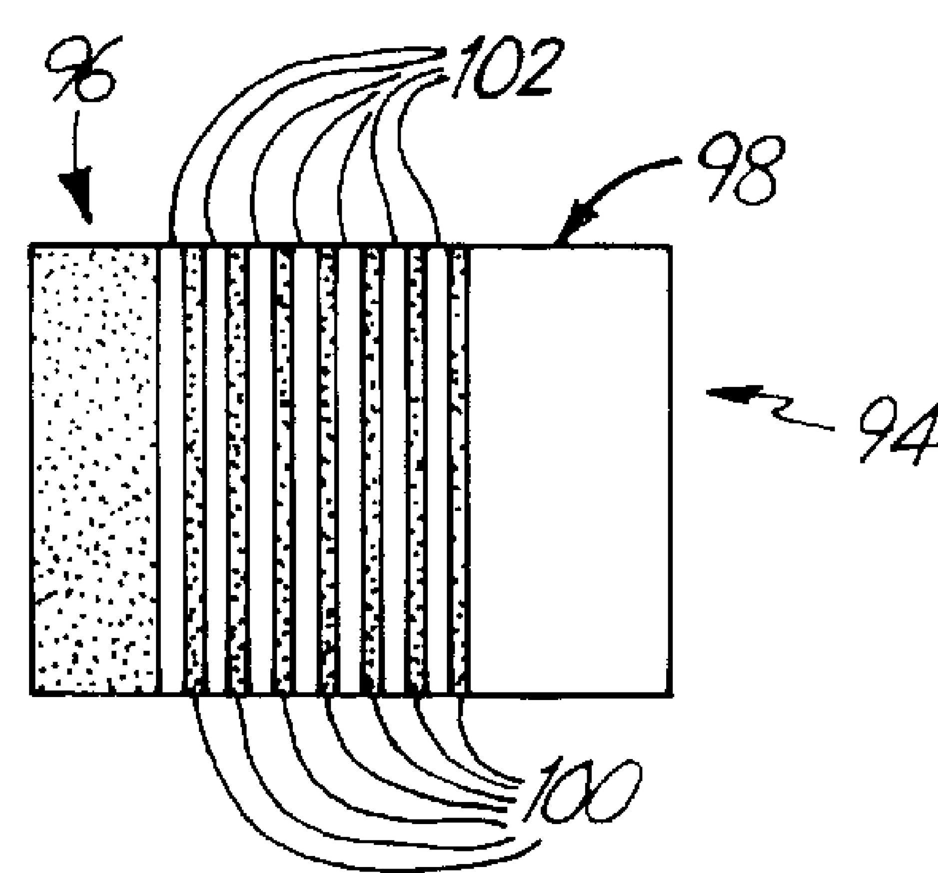


Fig. 5B

Fig. 6A

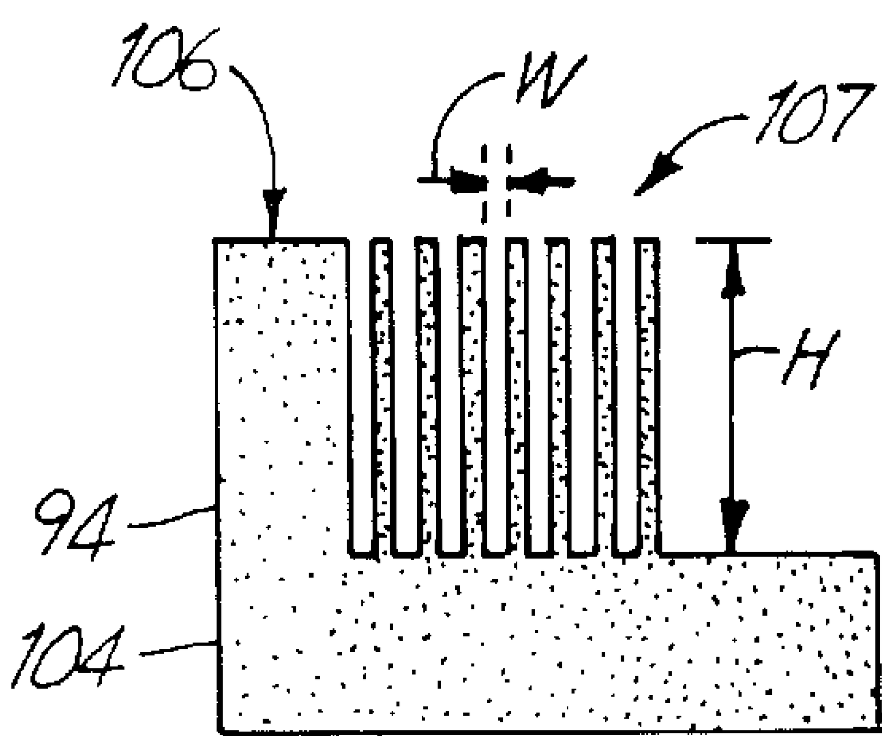


Fig. 6B

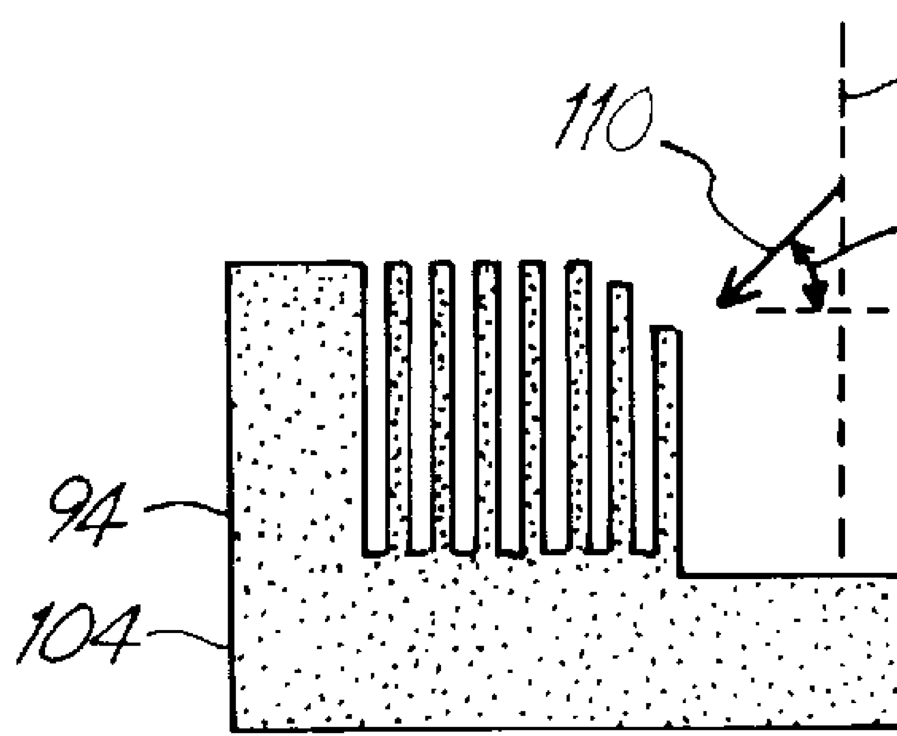
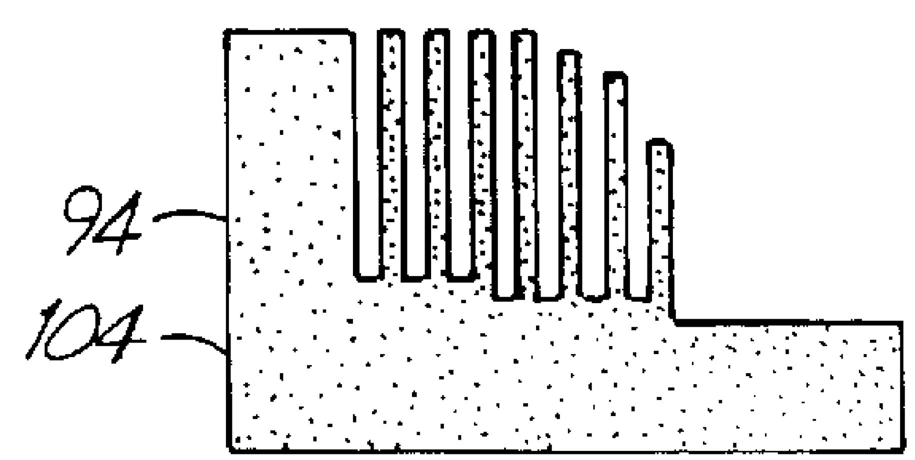


Fig. 6C



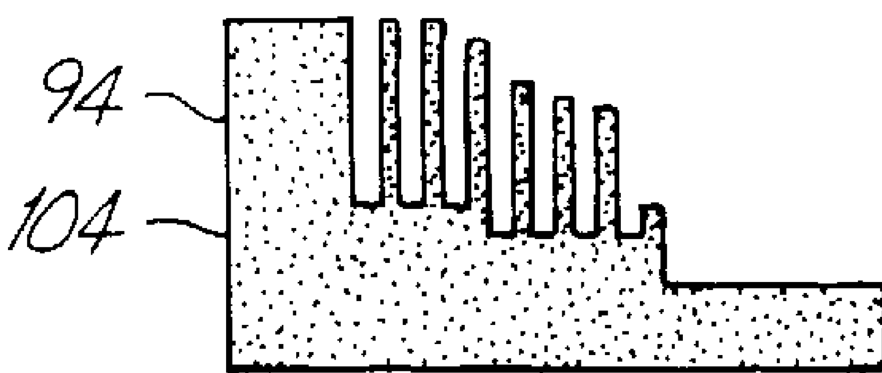


Fig. 6D

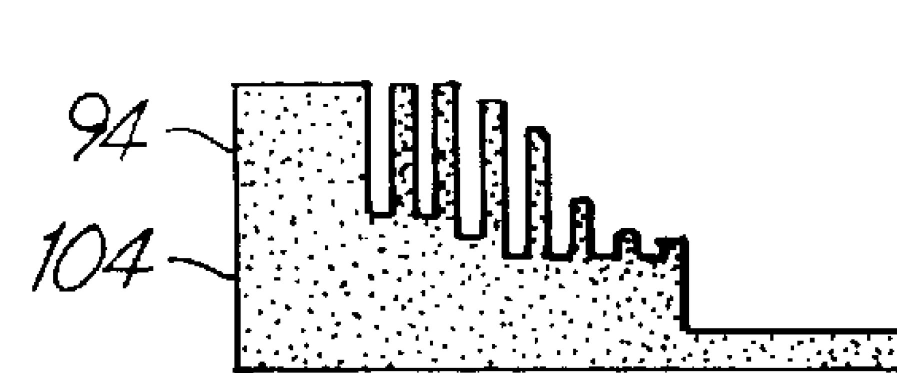


Fig. 6E

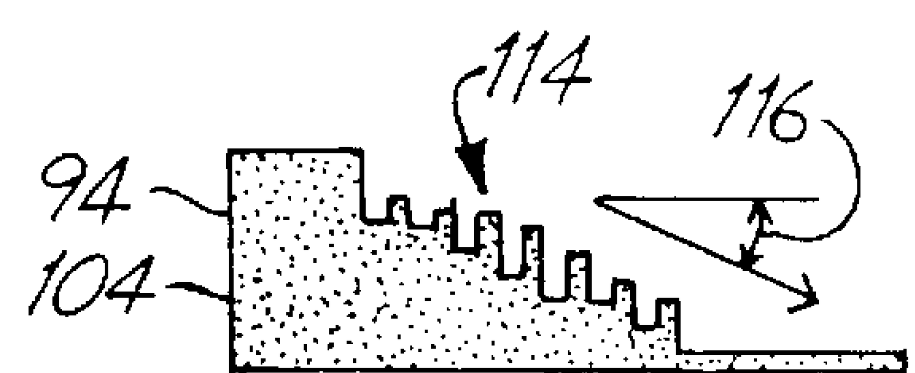


Fig. 6F

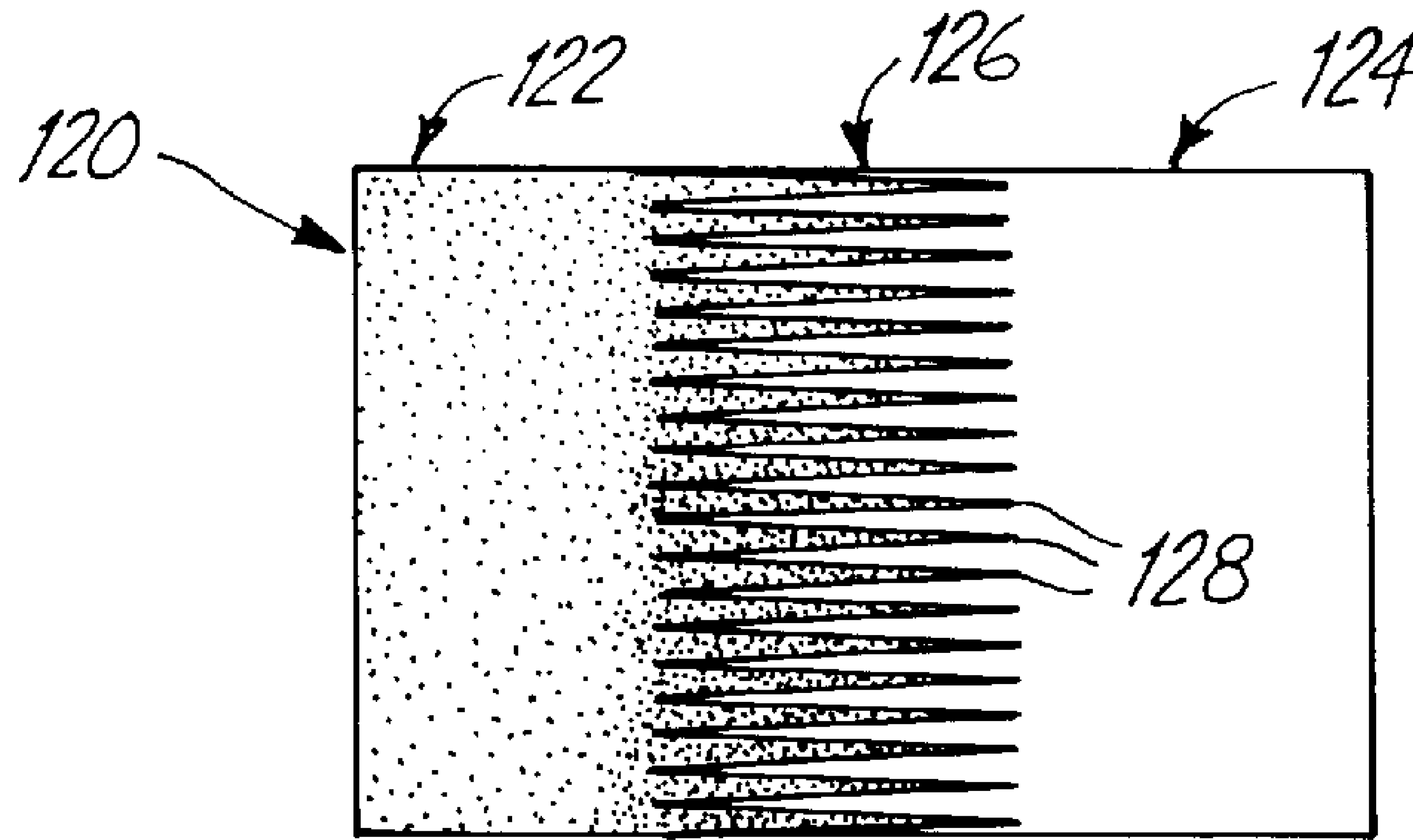


Fig. 7

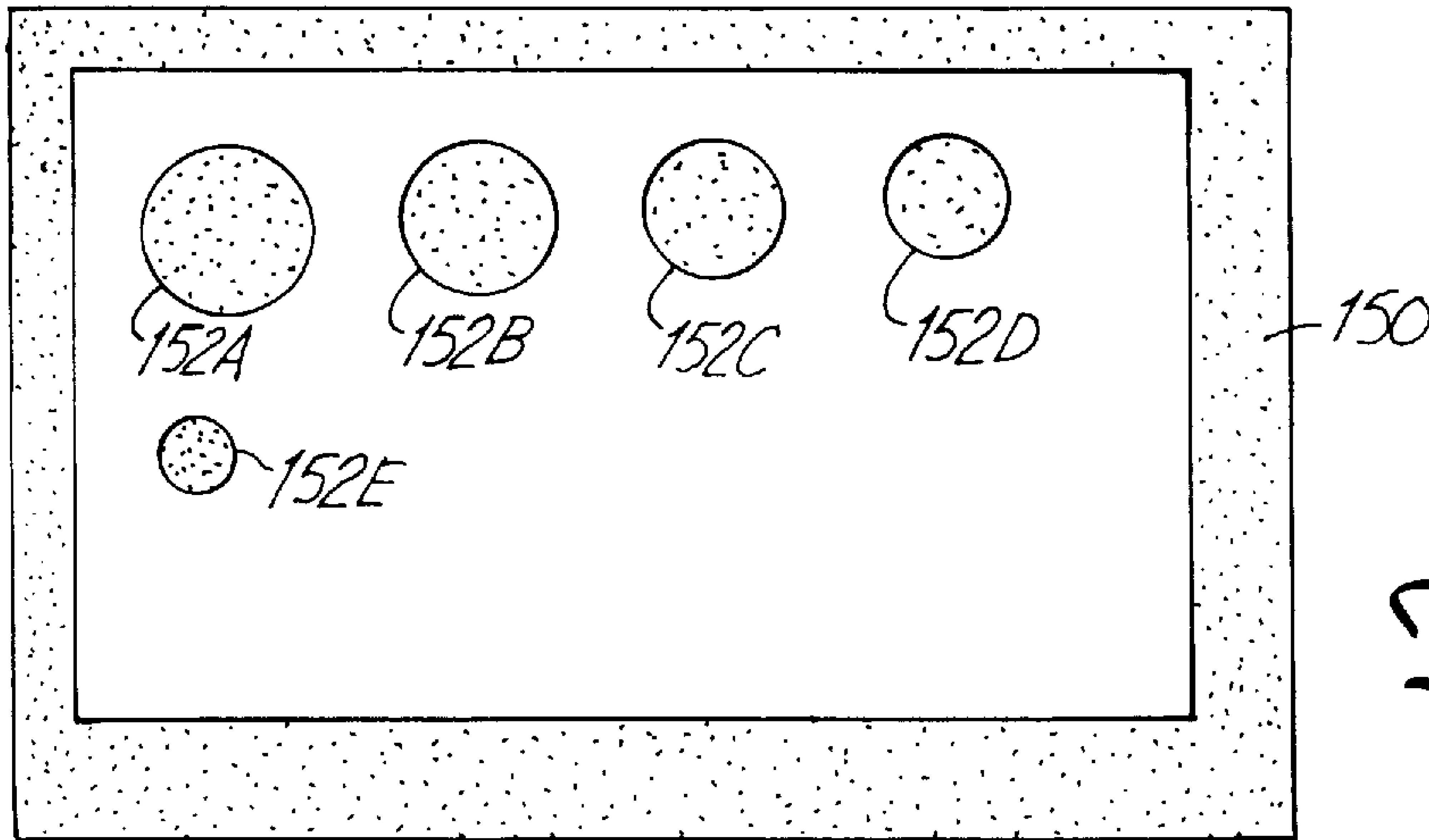


Fig. 8A

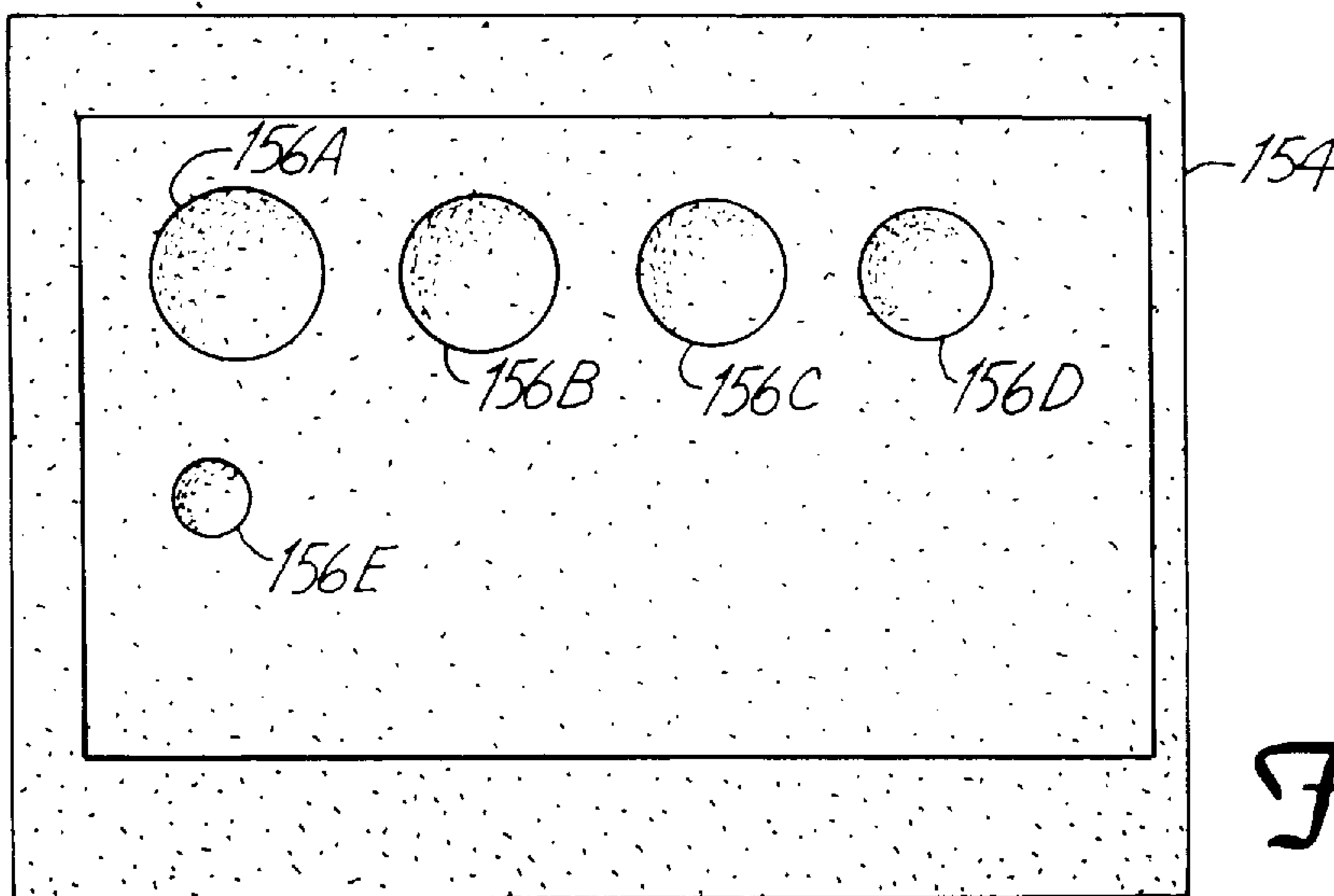


Fig. 8B

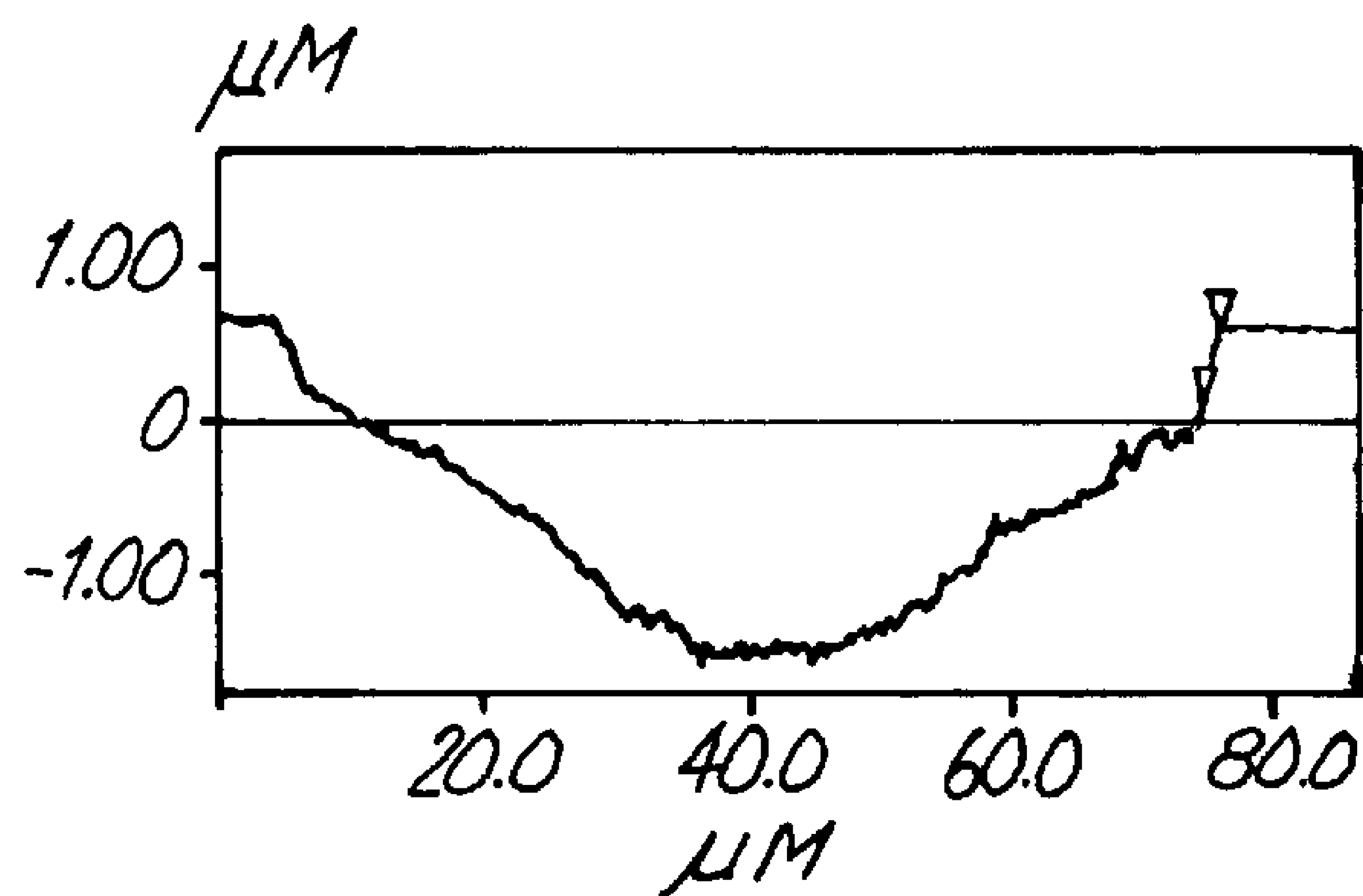


Fig. 8C

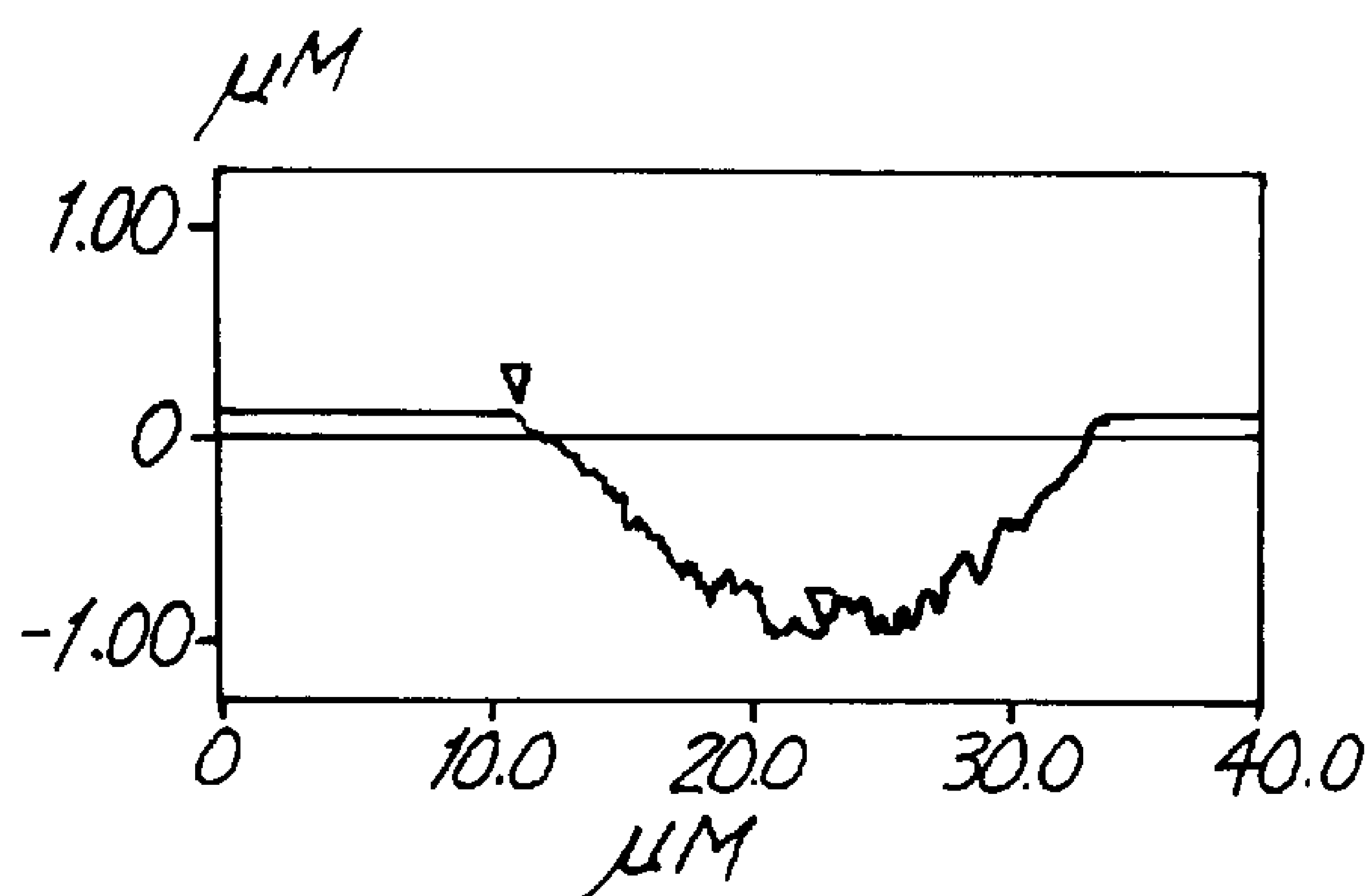


Fig. 8D

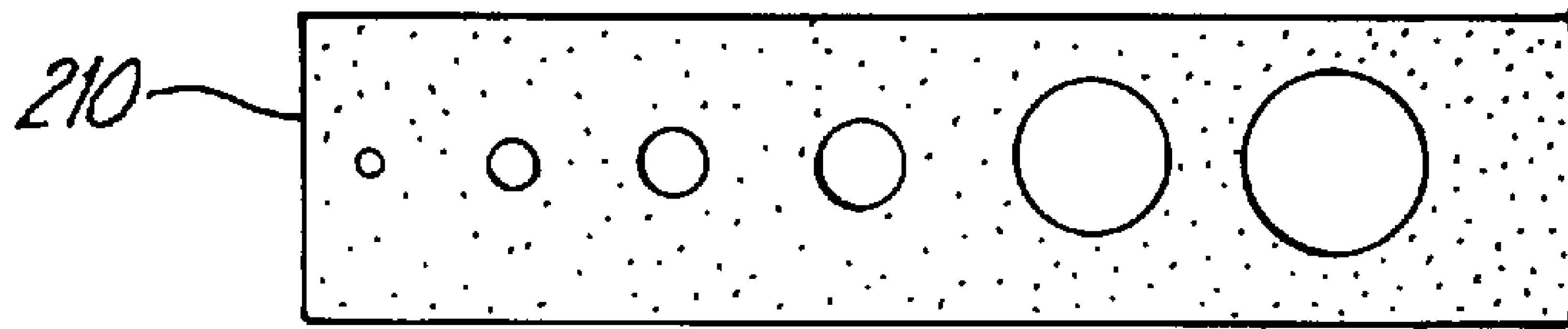


Fig. 9A

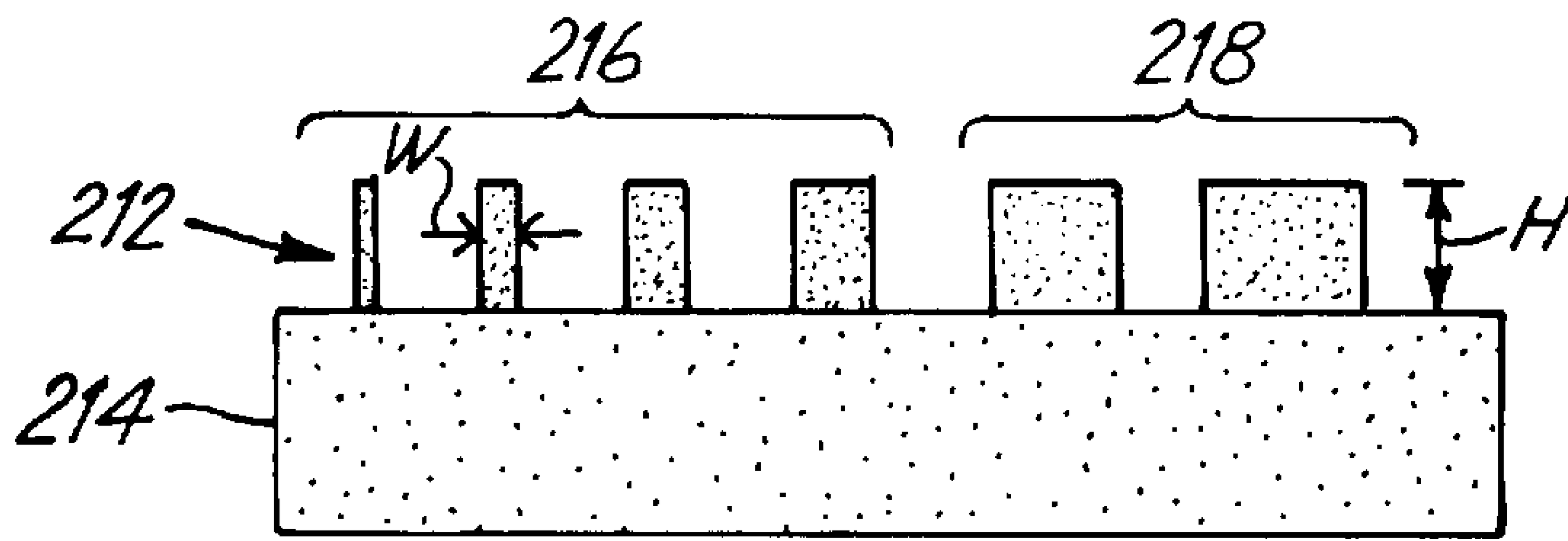


Fig. 9B

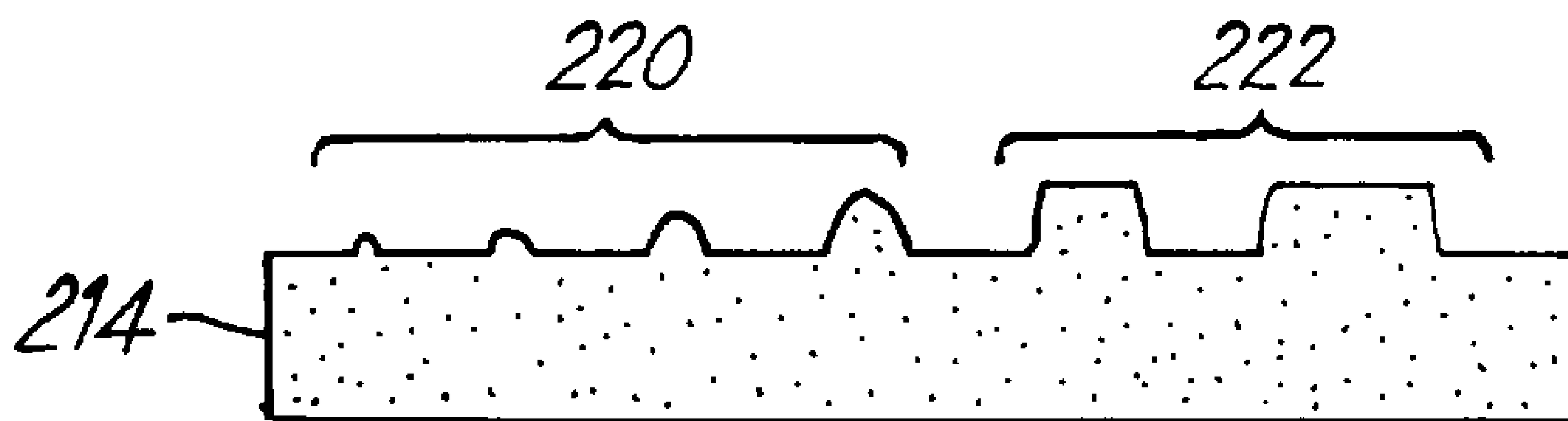


Fig. 9C

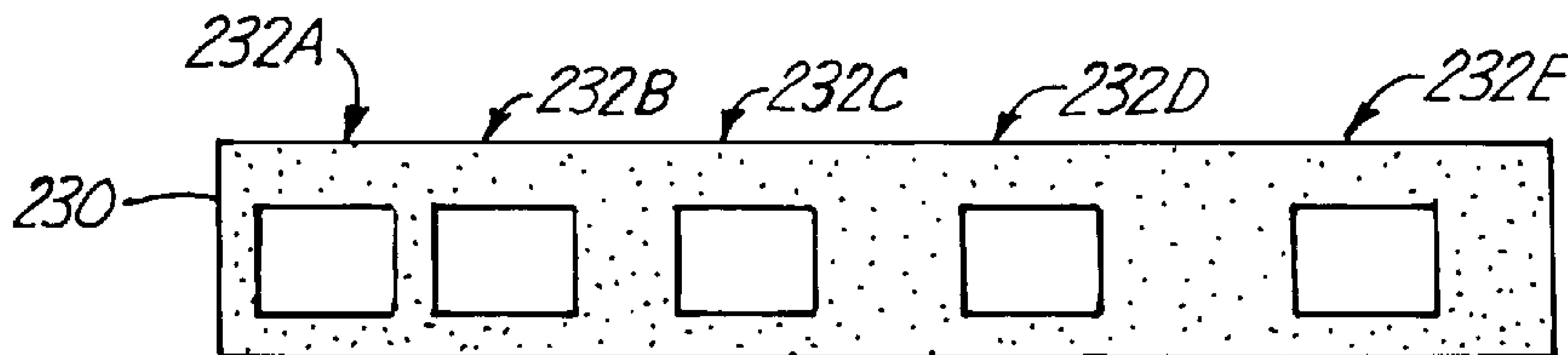


Fig. 10A

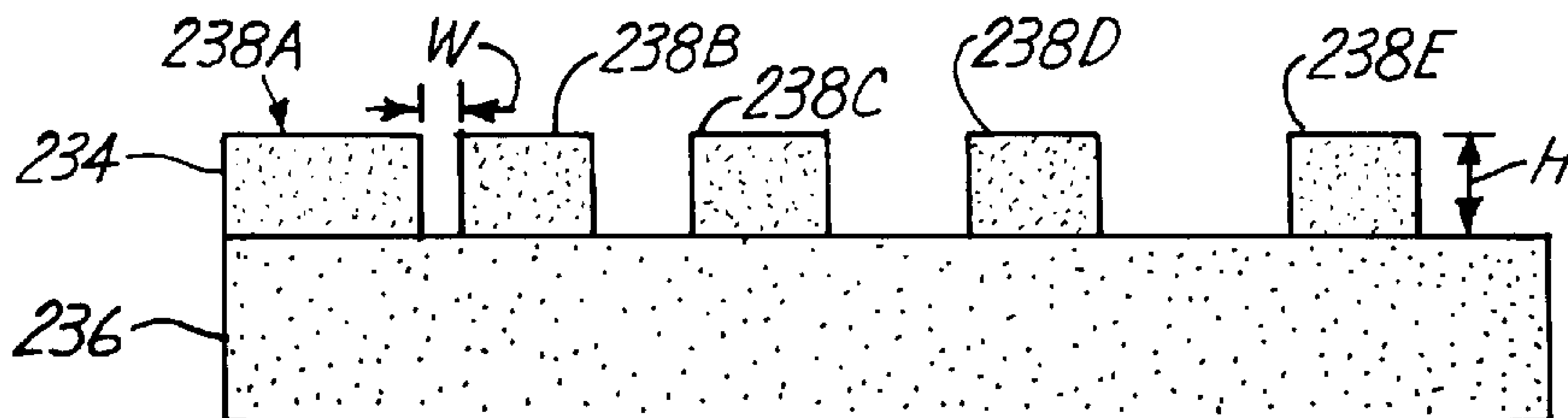


Fig. 10B

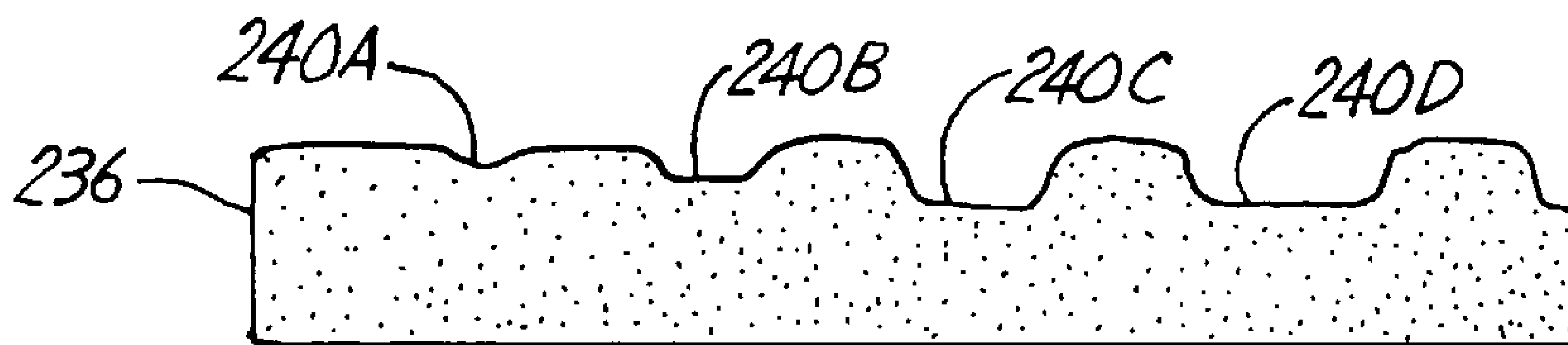


Fig. 10C

METHOD OF FABRICATING A CONTOURED SLIDER SURFACE FEATURE WITH A SINGLE MASK

BACKGROUND OF THE INVENTION

The present invention relates to disc drive data storage systems and, more particularly, to a method of fabricating a multiple depth surface feature on a hydrodynamic bearing slider with a single mask.

Disc drives of the "Winchester type" are well known in the industry. Such drives use rigid discs coated with a magnetizable medium for storage of digital information in a plurality of circular, concentric, data tracks. The discs are mounted on a spindle motor which causes the discs to spin and the surfaces of the discs to pass under respective head gimbal assemblies (HGAs). The HGAs carry transducers which write information to and read information from the disc surface. An actuator mechanism moves the HGAs from track to track across the surface of the discs under control of electronic circuitry. The actuator mechanism includes a track accessing arm and a load beam for each HGA. The load beam provides a preload force which presses the HGA toward the disc surface.

The HGA includes a hydrodynamic (e.g. air) bearing slider and a gimbal. The gimbal is positioned between the slider and the load beam to provide a resilient connection that allows the slider to pitch and roll while following the topography of the disc. The slider includes a slider body having an air bearing surface which faces the disc surface. As the disc rotates, the disc drags air under the slider along the air bearing surface in a direction approximately parallel to the tangential velocity of the disc. Skin friction on the air bearing surface causes the air pressure between the disc and the air bearing surface to increase which creates a hydrodynamic lifting force that causes the slider to lift and fly above the disc surface. The preload force supplied by the load beam counteracts the hydrodynamic lifting force. The preload force and the hydrodynamic lifting force reach an equilibrium based upon the hydrodynamic properties of the slider and the speed of rotation of the disc. The transducer is typically mounted at or near the trailing edge of the slider.

A conventional catamaran slider includes a pair of raised side rails which face the disc surface and form the air bearing surfaces. The raised side rails and other surface features on the slider are typically formed through a photolithography process followed by an ion milling or reactive ion etching process. Traditional photolithography processes use masks with hard edges to create well-defined patterns in the slider surface. Angled ion milling is often used to decrease redeposition of the milled substrate. Angled ion milling does decrease somewhat the slope of the edge feature in the slider surface. With angled ion milling, an ion beam is directed to the slider surface at an angle with respect to the slider surface. The ion beam is then rotated about an axis perpendicular to the slider surface. Angled ion milling results in well defined sidewalls with relatively large slopes. These edges tend to accumulate lubricant and debris during disc drive operation.

Photolithography techniques have also been used to recess portions of the pole tips of the read/write transducers at the trailing edge of the slider to improve performance, such as undershoot performance. The edges of the recesses can also serve as debris and lubricant collection areas.

There is a continuing need for improved fabrication processes of slider surface features which improve performance of the slider or read/write head while minimizing collection of debris and lubrication.

SUMMARY OF THE INVENTION

The fabrication process of the present invention forms a multiple depth surface feature on a surface of a hydrodynamic bearing slider with a single mask. The method includes applying a lithographic resist layer to the slider surface and forming the single mask with a mask pattern which includes a masked area, an unmasked area and an intermediate area between the masked area and the unmasked area. The lithographic resist layer can include a positive resist or a negative resist material. The lithographic resist layer is then exposed through the single mask and removed as a function of exposure to form a patterned resist layer and to thereby uncover portions of the slider surface within the patterned resist layer. The uncovered portions of the slider surface and the patterned resist layer are etched, with the uncovered portions being etched to a first depth below the slider surface. The intermediate mask area has a geometry that is unresolvable by one of the steps of exposing and etching such that an area of the slider surface corresponding to the intermediate mask area is etched to a second depth which is less than the first depth.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a perspective view of a hydrodynamic bearing slider, as viewed from its trailing edge and air bearing surface.

FIGS. **2**A–**2**F are cross-sections of a slider substrate, which illustrate the processing steps performed on the substrate according to one embodiment of the present invention.

FIG. **3** is a plan view of a portion of a photolithography mask according to the present invention.

FIGS. **4**A–**4**C are plan views of masks having various shaped masked features, in accordance with the present invention.

FIG. **5**A is a plan view of an aspect ratio limited photolithography mask, in accordance with the present invention.

FIG. **5**B is a plan view of an exposed photoresist pattern resulting from the mask shown in FIG. **5**A.

FIGS. **6**A–**6**F are cross-sections of a photoresist pattern and a slider substrate during progression through an ion milling process.

FIG. **7** is a plan view of a mask having saw-tooth shaped masked features.

FIGS. **8**A is plan view of a mask having a plurality of differently sized circular masked areas.

FIG. **8**B is a photograph of a slider substrate material having a plurality of milled holes resulting from the mask shown in FIG. **8**A.

FIGS. **8**C and **8**D are graphs illustrating profiles of two of the holes shown in FIG. **8**B.

FIGS. **9**A–**9**C illustrate a process for fabricating raised air bearing surface features according to the present invention.

FIGS. **10**A–**10**C illustrate a process for fabricating recessed air bearing surface features according to the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. **1** is a perspective view of a hydrodynamic bearing slider, as viewed from a trailing edge. Slider **10** includes a substrate **12** (e.g. ceramic), a leading edge **14**, a trailing edge **16**, raised side rails **18** and **20**, cross rail **22** and subambient

pressure cavity **24**. Raised side rails **18** and **20** form air bearing surfaces with inside and outside edges **26** and **28**. A typical fabrication process forms rails **18** and **20** with hard, well-defined edges. It has been found that these edges tend to accumulate lubricant and debris **30** during operation. Different air bearing shapes have different lubricant and debris accumulation properties.

Collection of lubricant and debris can be limited by forming the edges of side rails **18** and **20** with relatively smooth, shallow slopes. These shallow slopes can be fabricated according to the present invention with a single lithographic mask and etching process by providing the mask with additional features that are unresolvable by the imaging apparatus or the etching apparatus.

1. Resolution Limited Photolithography

FIGS. **2A–2F** are cross-sections of slider substrate **12** in schematic form, which illustrate the processing steps performed on the substrate according to one embodiment of the present invention. The dimensions shown in FIGS. **2A–2F** are greatly exaggerated for clarity. In FIG. **2A**, a positive photolithography resist ("photoresist") layer **40** is applied to surface **42** of substrate **12**. A variety of photoresist materials can be used, such as a diazonapththoquinone sulfonic ester, which is sold under the name NOVOLAK.

In FIG. **2B**, an imaging apparatus **44** exposes photoresist layer **40** through a photolithography mask **46**. Imaging apparatus **44** includes a light source **48** and a lens **50**, which are well known in the art. Mask **46** has a plurality of masked and unmasked areas which are arranged in a desired pattern for exposing photoresist layer **40**. For example, mask **46** includes masked areas **52** and unmasked area **54**. Light **58** generated by light source **48** is blocked by masked areas **52** and passes through unmasked area **54**. Lens **50** focuses light **58** passing through mask **46** onto photoresist layer **40** and thereby projects the desired pattern onto photoresist layer **40**.

Light **58** exposes portion **60** of photoresist layer **40** which correspond to unmasked area **54**, while portions **62** remain unexposed. Exposing portions **60** to light **58** induces a chemical change in the positive photoresist material which causes the portions to be susceptible to etching, as is well known in the art. Unexposed portions **62** resist etching.

According to the present invention, mask **46** includes additional, intermediate areas **56** between masked area **52** and unmasked areas **54**. Intermediate areas **56** have geometries that are beyond the resolution capability of imaging apparatus **44**. The light pattern passing through intermediate areas **56** becomes blurred as represented by wavy lines **64**. As a result, the blurred light pattern only partially exposes intermediate portions **66** of photoresist layer **40**.

In FIG. **2C**, photoresist layer **40** is removed through a chemical dissolution process as a function of the level of exposure to form a patterned photoresist. With the positive resist, fully exposed portion **60** is completely stripped from slider surface **42**, unexposed portions **62** remain on surface **42** and partially exposed portions **66** are partially stripped. After milling, the partial stripping of portions **66** provides sloping sidewalls between the stripped and unstripped resist portions.

In FIG. **2D**, the unstripped portions of the patterned photoresist layer **40** and the uncovered portions of slider surface **42** are etched to form the desired pattern in slider surface **42**. This pattern includes side rails **18** and **20**. Etching can include various types of etching, such as reactive or nonreactive ion milling for example. The sloping sidewall contour of partially stripped photoresist portions **66** are transferred to slider surface **42** to create smooth, sloped transitions along inside edges **26** of side rails **18** and **20**, shown in FIG. **1**.

After etching, a small portion of photoresist layer **40** remains on slider surface **42**. In FIG. **2E**, the remaining portions of photoresist layer **40** are removed, leaving the desired surface pattern in slider substrate **12**. Preferably, inside edges **26** have a maximum slope **70** of 20 degrees as measured from a plane defined by the air bearing surfaces of side rails **18** and **20**. Most preferably, the slope **70** is a maximum of 15 degrees. Further photolithography steps can then be performed to form additional surface features on slider substrate **12**. For example, in FIG. **2F** the subambient pressure cavity **24** has been formed between side rails **18** and **20**.

FIG. **3** is a plan view of a portion of mask **46** which illustrates one of the intermediate, partially masked areas **56** in greater detail. Intermediate area **56** is positioned between masked area **52** and unmasked area **54**. Intermediate area **56** includes a plurality of masked and unmasked features having a geometry that is smaller than the resolution of imaging apparatus **44**. The resolution capability of imaging apparatus **44** can be reduced by controlled defocus. Each vertical line **68** within intermediate area **56** represents a masked feature. The gaps between the vertical lines represent unmasked features. The width of each masked feature is smaller than the imaging capabilities of image apparatus **44** such that the masked features are not accurately reproduced on photoresist layer **40**.

In the embodiment shown in FIG. **3**, lines **68** have equal widths and are separated by distance D1 which progressively increases from masked area **52** toward unmasked area **54**. This provides a gradient in the level of light **58** passing through intermediate area **56**, which results in a gradient in the level of exposure in partially exposed portions **66** (shown in FIG. **2B**) from unexposed portion **62** toward unexposed portion **60**. At the left edge of intermediate area **56**, the mask lines **68** are spaced close together such that the photoresist layer **40** is mostly unexposed. At the right edge of intermediate area **56**, the mask lines **68** are widely spaced such that the photoresist layer **40** is mostly exposed. In an alternative embodiment, the spacing D1 between lines **68** remains equal, but the width of each line progressively decreases from masked area **52** toward unmasked area **54**. This also provides a gradient in the level of light passing through intermediate area **56**.

In the embodiment shown in FIGS. **2** and **3**, the photolithography mask includes additional, unresolvable mask features at the edge of the masked areas. The features are too small for the imaging system to image accurately. These optically, unresolvable features result in a continuous "grey" area at the edge of the masked areas. By varying the spacing, width and shape of the features, the extent of the "grey" area can be controlled. The unresolvable mask features can include shapes other than the lines shown in FIG. **3**. These shapes can include circles, dots, ovals, cross-hatches, diamonds, saw-teeth, scallops or other shapes. The shapes can form either the intermediate masked features or the intermediate unmasked features. The shapes can be arranged in any desired pattern with fixed or varying density.

FIG. **4A** is a plan view of a mask **72** having a plurality of circular shaped apertures **74** within intermediate area **56**. Apertures **74** increase in diameter from masked area **52** toward unmasked area **54** to provide increasing exposure from masked area **52** toward unmasked area **54**. Alternatively, apertures **74** can be sized equally and increase

in density toward unmasked area **54**. FIGS. **4**B and **4**C are plan views of masks **76** and **78** which have saw-tooth and scallop shaped masked features **80** and **82** within intermediate area **56**, respectively. These features decrease in density, from masked area **52** toward unmasked area **54**. Various other shapes and patterns can also be used in accordance with the present invention.

In an alternative embodiment, the photolithography mask is physically applied to the surface of the slider on top of, and in controlled proximity to, the layer of photoresist. In this embodiment, the proximity of the mask is decreased such that, due to the solid angle subtended by the light projected toward the mask, the fine feature resolution of the proximity exposure is inhibited by penumbral shadowing. The mask pattern cannot be accurately reproduced on the photoresist. The thickness of the mask causes the mask to be beyond the optical resolution of the imaging apparatus.

2. Aspect Ratio Limited Photolithography

The sloped edges can also be formed in the slider surface by adding features to the photolithography mask that are unresolvable by the etching process (e.g. ion milling), as opposed to the imaging process. While these features can be reproduced accurately onto the photoresist, the resulting etched pattern is altered by limitations of the etch process to transfer small features into the etched surface. As a result, the slider surface is formed with smooth or contoured, sloped transitions between milled and unmilled areas. The unresolvable mask features are defined such that the resulting pattern in the photoresist has a high aspect ratio in that the height of the photoresist is large compared to either the spacing between the photoresist features or the width of the photoresist features.

FIG. **5**A is a plan view of an aspect ratio limited photolithography mask **84** having additional masked features that are altered during transfer into the ion milled surface by process resolution limitations. Mask **84** includes a masked area **86**, an unmasked area **88** and an intermediate area **90**. Intermediate area **90** has a plurality of intermediate masked features **91** which are optically resolvable and can be accurately reproduced on the photoresist. However, the intermediate masked features **91** have a width (W) which is small compared to the height of the photoresist.

FIG. **5**B is a top plan view of an exposed photoresist pattern **94** resulting from the aspect ratio limited mask **84** shown in FIG. **5**A. The photoresist material includes a negative photoresist. In an alternative embodiment, a positive photoresist is used. Photoresist pattern **94** includes a fully exposed portion **96** corresponding to unmasked area **88**, an unexposed resist portion **98** corresponding to masked area **86** on mask **46** and a plurality of intermediate exposed and unexposed portions **100** and **102**, respectively, corresponding to intermediate area **90** of mask **84**.

FIGS. **6**A–**6**F are cross sections of the photoresist pattern **94** and slider substrate **104** during progression through the ion milling process. Following stripping, photoresist pattern **94** has a plurality of spaced resist features **106** and **107**, which correspond to exposed portions **96** and **100**, respectively, shown in FIG. **5**B. Resist features **106** and **107** have a height (H) on slider substrate **104** and are separated by gaps having the width (W).

Ion milling begins in FIG. **6**B. Ion beam **110** is directed toward photoresist pattern **94** and the uncovered surface of slider substrate **104** at an angle **6** which is measured from a vector within a plane parallel to the surface of slider substrate **104**. In one embodiment, ion beam **110** is rotated about an axis **112** which is perpendicular to the surface of slider substrate **104**. As discussed above, the intermediate photoresist features have a high aspect ratio (H/W). In a preferred embodiment, the aspect ratio (H/W) is defined as $H/W \geqq \tan \theta$. As seen by the progression through FIGS. **6**B–**6**F, the intermediate resist features **107** initially "shadow" one another from right to left. As the ion milling progresses, the resist on the right of the figures becomes milled and no longer shadows the adjacent features. The resist features on the right are milled at a faster rate than the resist features on the left, which creates a sloped edge **114** in the surface of slider substrate **104**. Edge **114** has a slope **116** which is preferably a maximum of 20 degrees and, most preferably, a maximum of 15 degrees as measured from the slider surface. Although the process shown in FIGS. **6**A–**6**F are discussed with reference to ion milling, other directed beam anisotropic etching processes can also be used to achieve the shadowing effect caused by the high aspect ratio photoresist features. Although FIGS. **6**A–**6**F show the milling process creating sharp features in the slider surface, the topography of the features are much more rounded.

The intermediate resist features can have a variety of shapes in addition to the rectangles shown in FIGS. **5** and **6**. For example, the intermediate resist features can include circles, dots, ovals, cross hatches, diamonds, saw-teeth, scallops and other shapes. FIG. **7** illustrates a mask **120** which creates intermediate resist features having a saw-tooth shape. Mask **120** includes a masked area **122**, an unmasked area **124** and an intermediate area **126**. Intermediate area **124** has a plurality of saw-tooth shaped intermediate mask features **128**. As in the embodiment shown in FIGS. **5** and **6**, intermediate masked features **128** create patterns in the photoresist which shadow one another during the initial stages of the ion milling process.

3. Example

FIG. **8**A is a schematic of a mask **150** having a plurality of differently sized circular masked areas **152**A–**152**E. FIG. **8**B is a photograph of a slider substrate material **154** having a plurality of milled holes **156**A–**156**E resulting from the mask shown in FIG. **8**A. The largest hole **156**A is 60 micrometers in diameter. The smallest hole **156**E is 22 micrometers in diameter. The photoresist used during the milling process was about 30 micrometers high. Consequently, the aspect ratio (height of photoresist to width of hole) of the largest resist feature was 0.5 and the aspect ratio of the smallest resist feature was 1.35. The ion milling angle θ was 45 degrees ($\tan(\theta)=1.0$).

FIG. **8**C is a plot of the cross section of the largest hole **156**A. The edge of hole **156**A has a slope of 18–21 degrees as measured from the surface adjacent the hole. The center of hole **156**A has a slope of about 3 degrees.

FIG. **8**D is a plot of a cross section of the smallest hole **156**E. The edge of hole **156**E has a constant slope of about 5 degrees. The slope of hole **156**E is much less than the slope of hole **156**A because of the higher aspect ratio. In other words, the height of the photoresist surrounding hole **156**E was sufficiently large as compared to the diameter of the hole that the photoresist shadowed the hole during the angled ion milling process. Initially, the ions were unable to reach the substrate surface until the edge of the photoresist was milled to less than the width of the hole.

The resolution limited and aspect ratio limited photolithography fabrication processes of the present invention permits a transition from non-milled to milled areas on the slider surface to extend over a controlled width. By shaping the edges of the slider surface in a controlled manner, debris and lubricant accumulation can be minimized during disc

drive operation. Also, the fabrication processes of the present invention allow the slider surface to be milled at multiple depths with a single mask pattern and photoresist. This can be used to form the edges of air bearing surfaces or edges of other features on the slider surface. For example, the fabrication processes can be used to perform multiple-depth patterning of pole tips in the read/write head to improve performance of the head while limiting debris and lubricant collection. Pole tips have been contoured to provide undershoot reduction. Current processes only permit single level pole patterning depths. With the present invention, pole patterning features can be created with complex contours to optimize the edges of the poles for reduced debris and lubricant accumulation.

4. Use of Aspect Ratio Limited Photolithography for Creating Raised or Recessed Air Bearing Features

In another aspect of the present invention, the aspect ratio limited photolithography process can be used to created raised or recessed air bearing surface features. According to the present invention, photolithographic techniques are used to create photoresist patterns with high aspect ratios that cannot be reproduced during the ion milling process. Consequently, the resulting surface features on the slider have curved edges and contoured topographies. The contoured typographies create reduce debris collection and provide strength to the protruding surfaces.

FIGS. **9**A–**9**C illustrate a process for fabricating raised air bearing surface features according to the present invention. FIG. **9**A is a plan view of a mask **210** having a plurality of circular, unmasked apertures of various diameters. FIG. **9**B is a cross section of a patterned photoresist layer **212** on the surface of a slider substrate **214**, which results from the mask shown in FIG. **9**A. FIG. **9**C is a cross section of slider substrate **214** after milling.

Patterned photoresist layer **212** includes a plurality of resist features **216** and **218** having a height (H) and a width (W). The aspect ratio of each feature is defined as H/W. Resist features **216** have high aspect ratios (greater than 1.5) and are thus not completely resolvable during the ion milling process. Since the aspect ratios of resist features **216** are high, the resist features are milled from the top and sides which causes surface features **220** formed in substrate **214** to become rounded.

Resist features **218** have conventional, lower aspect ratios (less than 1.0). Resist features **218** remain on the surface of substrate **214** during the entire milling process, which prevents any substrate removal. The corresponding surface features **224** formed in substrate **214** therefore have sharp sidewalls.

FIGS. **10**A–**10**C illustrate a fabrication process for fabricating recessed features, as opposed to raised features on the air bearing surface. FIG. **10**A is a plan view of a mask **230** having a plurality of unmasked apertures **232**A–**232**E. Apertures **232**A and **232**B are spaced closely together which causes the resulting photoresist features to shadow one another during the milling process and therefore create surface features in the slider surface with rounded slopes. In contrast, apertures **232**B–**232**E are spaced further apart.

FIG. **10**B is a cross section of a patterned photoresist layer **234** on the surface of a slider substrate **236**, which results from the mask shown in FIG. **10**A. Patterned photoresist layer **234** includes resist features **238**A–**238**E corresponding to apertures **232**A–**232**E. Resist features **238**A–**238**E have a height (H) and are separated by a gap having a width (W).

FIG. **10**C is a cross section of substrate **236** after milling. Recessed features **240**A–**240**D are formed in substrate **236** at the gaps between resist features **238**A–**238**E. Since the gap between resist features **238**A and **238**B is small compared to the height H, recessed feature **240**A has shallow, sloping sidewalls. Since the gap between resist features **238**B and **238**E is larger, recessed features **240**B–**240**D have relatively sharply defined, steep sidewalls. There is little or no shadowing between resist features **238**B–**238**E.

Although the present invention has been described with reference to preferred embodiments, workers skilled in the art will recognize that changes may be made in form and detail without departing from the spirit and scope of the invention. For example, the present invention has been described with respect to a photolithography process. However, the present invention is equally applicable to other lithography processes such as electron beam and x-ray lithography.

What is claimed is:

1. A method of fabricating a multiple depth feature on a surface of a hydrodynamic bearing slider, the method comprising:

applying a lithographic resist layer to the slider surface;

forming a single mask having a mask pattern which includes a masked area, an unmasked area and an intermediate area between the masked area and the unmasked area;

exposing the lithographic resist layer through a single mask;

removing the lithographic resist layer as a function of exposure to form a patterned resist layer and to thereby uncover portions of the slider surface within the patterned resist layer;

etching the uncovered portions of the slider surface and the patterned resist layer, with the uncovered portions being etched to a first depth below the slider surface; and

wherein the step of forming the single mask includes providing the intermediate area with a geometry that is unresolvable by one of the steps of exposing and etching such that an area of the slider surface corresponding to the intermediate mask area is etched to a second depth below the slider surface which is less than the first depth.

2. The method of claim **1** wherein:

the step of forming the single mask comprises defining the geometry of the intermediate mask area with a linear dimension; and

the step of exposing comprises projecting the single mask onto the resist layer with an imaging apparatus having a resolution that is larger than the linear dimension such that a first portion of the lithographic resist layer corresponding to the unmasked area is exposed at a first exposure level, a second portion of the lithographic resist layer corresponding to the masked area is unexposed and a third portion of the lithographic resist layer corresponding to the intermediate area is partially exposed at a second exposure level which is lower than the first exposure level.

3. The method of claim **1** wherein:

the step of applying comprises applying to the slider surface a lithographic resist layer having a height, H;

the step of forming the single mask comprises defining the geometry of the intermediate mask area such that the step of removing forms the patterned resist layer with first and second resist features on the slider surface which are separated by a gap having a width, W; and

the step of etching comprises performing a directed, anisotropic etch at an angle θ which is measured from a vector within a plane of the slider surface, wherein $H/W \geqq \tan \theta$.

4. The method of claim **1** wherein:

the step of removing comprises forming the patterned resist layer with a resist feature having a height, H, and a width, W; and

the step of etching comprises performing a directed, anisotropic etch at an angle θ which is measured from a vector within a plane of the slider surface, wherein $H/W \geqq \tan \theta$.

5. The method of claim **1** and further comprising:

physically applying the single mask to the lithographic resist layer, the mask having a height, H;

the step of forming the intermediate mask area comprises forming intermediate masked and unmasked areas, wherein the intermediate masked areas are separated by a gap having a width, W, and selecting the height, H, and the width, W, such that the step of exposing exposes the lithographic resist layer at the intermediate unmasked areas less than the unmasked area of the mask pattern and more than the masked area of the mask pattern.

6. The method of claim **1** and further comprising forming the intermediate mask area with a shape selected from the group consisting of circle, oval, cross-hatch, diamond, saw-tooth and scallop.

7. The method of claim **1** wherein the step of etching comprises etching the area of the slider surface corresponding to the intermediate mask area such that the slider surface has a vertical slope which is a maximum of fifteen degrees measured from a plane defined by the slider surface.

8. A method of fabricating a hydrodynamic bearing slider to form a vertically contoured feature on a surface of the slider with a single mask, the method comprising:

applying a lithographic resist layer to the slider surface;

exposing the resist layer through the single mask such that a first portion of the resist layer is exposed at a first exposure level, a second portion of the resist layer is unexposed and a third portion of the resist layer, which is positioned between the first and second portions, is partially exposed at a second exposure level which is lower than the first exposure level;

removing the resist Layer as a function of exposure to uncover a portion of the slider surface, wherein the third portion of the resist layer is only partially stripped; and

etching the resist layer and the uncovered portion of the slider surface.

9. The method of claim **8** and further comprising:

forming the mask with a fully masked portion,

a fully unmasked portion and an intermediate portion between the fully masked portion and the fully unmasked portion, wherein the intermediate portion has a geometry of intermediate masked and unmasked areas which has a linear dimension; and

the step of exposing comprises exposing the resist layer through the single mask with an imaging apparatus having a resolution that is larger than the linear dimension so that the intermediate portion is resolved inaccurately by the imaging apparatus.

10. The method of claim **9** wherein the step of forming the mask comprises:

forming the intermediate masked and unmasked areas so that a distance between intermediate masked areas is smaller than the resolution of the imaging apparatus.

11. The method of claim **10** wherein forming the intermediate masked and unmasked areas comprises progressively increasing the distance between the intermediate masked areas from the fully masked portion toward the fully unmasked portion to increase exposure of the resist layer progressively from the fully masked portion toward the fully unmasked portion.

12. The method of claim **9** wherein the step of forming the mask comprises:

forming the intermediate masked and unmasked areas so that the intermediate masked areas have a width that is smaller than the resolution of the imaging apparatus.

13. The method of claim **12** wherein forming the intermediate masked and unmasked areas comprises progressively decreasing the width of the intermediate masked areas from the fully masked portion toward the fully unmasked portion to increase exposure of the resist layer progressively from the fully masked portion toward the fully unmasked portion.

14. The method of claim **9** wherein the step of forming the mask comprises varying the shape of the intermediate masked areas from the fully masked portion toward the fully unmasked portion to increase exposure of the resist layer progressively from the fully masked portion toward the fully unmasked portion.

15. A method of fabricating a multiple depth feature on a surface of a disc head slider with a single lithographic resist, the method comprising:

forming first and second lithographic resist features on the slider surface which are separated by a gap, the resist features covering a first portion of the slider surface and leaving a second portion of the slider surface uncovered within the gap, wherein the resist features have a height, H, and the gap has a width, W; and

performing a directed beam anisotropic etch on the resist features and the second, uncovered portion of the slider surface at an angle θ, which is measured from a vector within a plane defined by the slider surface, wherein $H/W \geqq \tan \theta$.

16. The method of claim **15** wherein the multiple depth feature comprises a raised surface, a recessed surface and an edge between the raised and recessed surfaces and wherein the step of forming the first and second lithographic resist features comprises:

forming a plurality of longitudinal resist features generally parallel to the edge and separating the plurality of resist features from one another gaps having the width, W.

17. The method of claim **15** wherein the multiple depth feature to be fabricated comprises a raised surface, a recessed surface and an edge between the raised and recessed surfaces and wherein the step of forming the first and second lithographic resist features comprises:

forming a patterned lithographic resist layer on the slider surface which covers the surface to be raised and uncovers the surface to be recessed: and

forming a sawtooth pattern in the lithographic resist layer along the edge, wherein individual teeth within the sawtooth pattern define the first and second resist features and a distance between the individual teeth defines the gap.

18. The method of claim **15** wherein the multiple depth feature to be fabricated comprises a raised surface, a recessed surface and a sloped edge between the raised and recessed surfaces and wherein the step of forming the first and second lithographic resist features comprises:

forming a patterned lithographic resist layer on the slider surface which covers the surface to be raised and uncovers the surface to be recessed: and

forming a plurality of apertures in the patterned resist layer along the edge, wherein the apertures have the width, W.

19. The method of claim **15** wherein the multiple depth feature to be fabricated comprises a raised surface, a recessed surface and a sloped edge between the raised and recessed surfaces and wherein the step of forming the first and second lithographic resist features comprises:

forming a patterned lithographic resist layer on the slider surface which covers the surface to be raised, uncovers the surface to be recessed and includes a plurality of resist features which are spaced from each other by the width, W.

20. The method of claim **15** wherein the step of performing a directed, anisotropic etch comprises ion milling.

21. The method of claim **20** wherein the step of ion milling comprises directing an ion beam toward the slider surface at the angle θ and rotating the ion beam along a circular path.

22. A method of fabricating a surface feature on a bearing surface of a hydrodynamic bearing slider, the method comprising:

forming a lithographic resist pattern on the bearing surface, the pattern having a resist feature corresponding to the surface feature to be fabricated and the resist feature having a dimension; and

performing a directed beam anisotropic etch on the lithographic resist pattern and the bearing surface, which is incapable of accurately reproducing the dimension on the bearing surface so that the corresponding surface feature has a rounded contour with sloping side walls.

23. The method of claim **22** wherein:

forming the lithographic resist pattern comprises forming the resist feature with a height, H, and a width, W, wherein $H/W \geqq 1.5$; and

performing the step of etching comprises etching at an angle θ measured from a vector in a plane defined by the bearing surface.

24. The method of claim **22** wherein:

forming the lithographic resist pattern comprises forming first and second resist features having a height, H, and separated by a gap having a width, W; and

performing the step of etching comprises etching at an angle θ measured from a vector in a plane defined by the bearing surface, wherein $H/W \geqq \tan \theta$.

25. The method of claim **22** wherein:

forming the lithographic resist pattern comprises forming first and second features which have a height, H, and are spaced by a gap having a width, W, wherein the first and second resist features cover a portion of the bearing surface; and

performing the step of etching comprises etching at an angle θ measured from a vector in a plane defined by the bearing surface, wherein $H/W \geqq \tan \theta$.

26. A method of contouring a surface of a hydrodynamic bearing slider, the method cormprising:

applying a lithographic resist layer to the slider surface;

providing a single lithographic mask; and

forming a vertically tapered feature on the slider surface as a function of the mask pattern by exposing the lithographic resist layer through the single lithographic mask with an exposure level that is graduated along an area of the lithographic resist layer corresponding to the vertically tapered feature, removing the lithographic resist layer as a function of the exposure level to form a patterned resist layer and to uncover portions of the slider surface within the patterned resist layer, and etching the uncovered portions of the slider surface and the patterned resist layer to form the vertically tapered feature with a varying depth.

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